Overbalanced wheels: Leonardo's studies of perpetual motion in context

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Abstract

This paper centres on Leonardo's studies of perpetual motion. It sets a context for his interest in the subject, from his early Florentine years to his mature period Sforza Milan and the Florentine Republic, exploring links with his all-encompassing interest in motion, from geometry and mechanical motion to the flight of birds and human movement. It then focuses on crucial examples of his perpetual motion drawings in the Codex Atlanticus and Codex Forster, unveiling unexpected similarities with key artistic drawings in graphic techniques, work method and thinking process.

Motion occupies a central place in Leonardo's art and science. At the core of his studies of motion is his search for a perpetual motion machine. His most developed perpetual motion studies took the form of overbalanced wheels, which would work with total efficiency and be self-sufficient ad infinitum [Fig .1]. The idea was to create a disruption of equilibrium by making one side of the wheel overweigh the other. Like the arms of a balance, equal weights equally distant from the fulcrum would be in equilibrium. When there was a change in the distance from the fulcrum or in the amount of weight, there would be a proportional change in the

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mathematical centre of the system; the need to regain the lost equilibrium would produce motion and make the wheel turn.

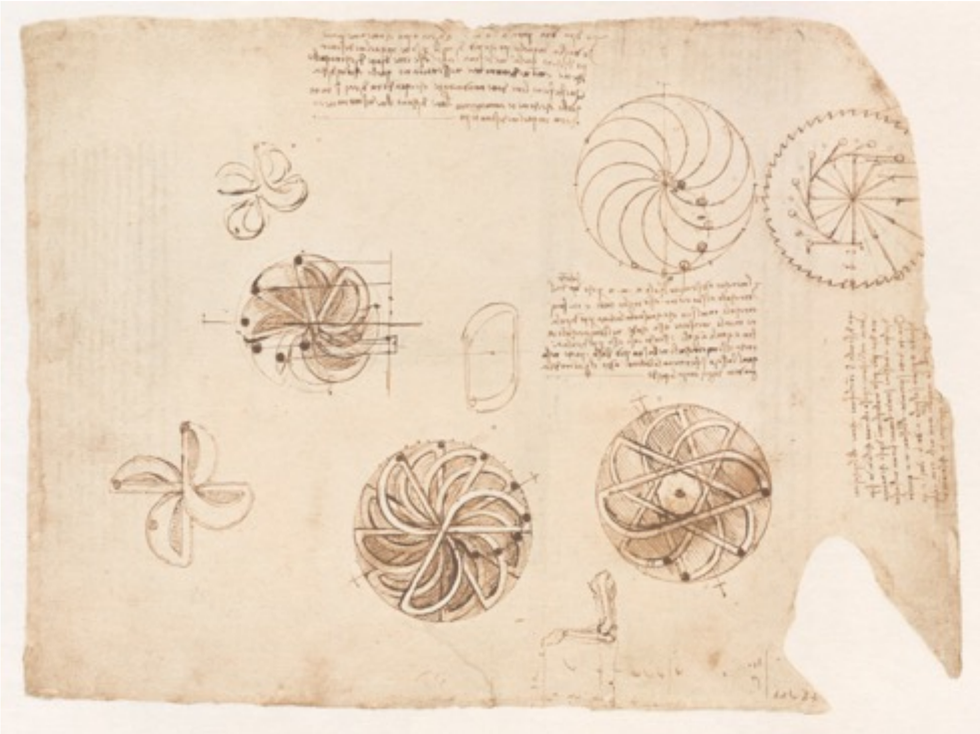

Figure1
Leonardo da Vinci
Studies of overbalanced wheels, Codex Atlanticus, f. 1062r
Pen and ink, c. 1495
Photo credit Veneranda Biblioteca Ambrosiana / Metis e Mida Informatica / Mondadori Portfolio

The quest to develop a perpetual motion machine seems to have occupied natural philosophers and engineers from as early as the Middle Ages[2]. If some of Leonardo's perpetual motion studies relate to designs explored by earlier artists and engineers, others show his own developments and original thinking. His interest in grasping the principles underlying a continuous change in the arrangement of weights to retain the momentum

2 See BERNARDONI, Andrea. "Against nature: Studies and experimentation on perpetual motion before Leonardo". In: BERNARDONI, *op. cit.*, 2019, pp. 12-23.

necessary for making a wheel turn is, to some extent, comparable to his engagement with the classical problem of the “squaring of the circle” in which a circle had to be transformed into a square while retaining the same area. In connection with this problem, Leonardo also composed a book “On transformation” (*De trasformazione*)[3], in which he sought to transform one body into another without subtraction or addition of material, leading him to explore graphically “the process of unlimited ways of squaring curvilinear surfaces”[4]. Yet, as a firm advocate of the direct study of nature through observation and experimentation, Leonardo was well-aware of the difference between theoretical knowledge and its application in the physical world. In the case of a perpetual motion wheel, factors such as the forces of gravity and friction, as well as the materiality of a given structure, had to be taken into account. So, unlike the geometrical problem of the squaring of the circle, which Leonardo declared to have solved even if he continued to explore solutions[5], he openly stated the impossibility of perpetual motion, comparing the search for the perfect, self-sufficient machine that would work indefinitely to the vain attempts of alchemists: “Oh seekers after perpetual motion, how many vain designs and similar things you have created! Go and take company with those who seek after gold”[6].

In spite of Leonardo’s statement, his perpetual motion studies were neither few nor isolated. They have not yet been investigated consistently and

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3 See Codex Forster I (1), f. 3r. The book is dated by Leonardo “1505”. For the manuscript, see Leonardo da Vinci, **I codici Forster I–III nel Victoria and Albert Museum**, Rome: Reale Commissione Vinciana, 1930-36; and Leonardo da Vinci, **Il Codice Forster I, Il Codice Forster II, Il Codice Forster III**, transc. A. Marinoni, Florence: Giunti, 1992.

4 For Leonardo’s statement, see Codex Atlanticus, f. 272v. For related studies, see for instance Codex Atlanticus, ff. 373r, 307v, 455r, in BARONE, Juliana, **Studies of motion. Drawings by Leonardo from the Codex Atlanticus**, Novara: De Agostini, 2011, entries 28-30, pp. 34-36. For the manuscript, see Leonardo da Vinci, **Il Codice Atlantico di Leonardo da Vinci nella Biblioteca Ambrosiana di Milano**, transc. A. Marinoni, Florence: Giunti, 1973-75.

5 See Codex Madrid II, f. 112r. Leonardo da Vinci. **The Madrid codices of Leonardo da Vinci**. Transc. and transl. L. Reti. New York: Biblioteca Nacional, 1974.

6 Forster II, f. 92v. Similar negative statements about perpetual motion appear in Forster II, f. 89v; MS A, f. 22v; MS Madrid I, first flyleaf and f. 148r. For MS A and the French manuscripts, see Leonardo da Vinci, **Les manuscrits de Léonard de Vinci. [A-M]**, transcr. and transl. C. Ravaisson-Mollien, Paris: Institut de France, 1881-91.

even less so in the broader context of his oeuvre. My undergoing study of them with Andrea Bernardoni has revealed that his perpetual motion drawings are not only numerous, but are also rendered in a variety of media, degree of finish and dimension[7]. As far as we have been able to estimate, they total some thirty sheets, several with more than one drawing, and are spread across various manuscripts, including the Codices Atlanticus, Arundel, Madrid I and II, Forster I, II, III, and MSS A, E and H. They are found in sheets dating from c. 1480, such as the little sketch in the Codex Atlanticus, f. 1117rb, drawn in connection with studies of military devices during his first Florentine period[8], to others as late as c. 1515, including two sheets from the Codex Atlanticus, ff. 267r and 337r, addressing the issue of force in pulleys, wheels and waterwheels[9].

While Leonardo can be shown to have held an enduring interest in perpetual motion, his most notable involvement with the subject occurred in Milan at the Sforza court (c. 1481-99) and had a significant repercussion in his second Florentine sojourn (1500-c. 1508). It is no coincidence that it is during these very periods that we witness Leonardo deepening his knowledge of mathematics and geometry, as well becoming increasingly involved with practical matters concerning hydraulic engineering, which undoubtedly contribute to his deep reflection on hydrodynamic laws and

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7 For studies of Leonardo and perpetual motion, see KEMP, Martin, **Leonardo da Vinci**, London: Yale University Press, 1989, entries 59-60, pp. 126-27; GALLUZZI, Paolo, "La chimera del moto perpetuo", in: GALLUZZI, Paolo (Ed.), **La mente di Leonardo nel laboratorio del genio universale**, Florence: Giunti, 2006, pp. 250-51; BARONE, Juliana, **Leonardo da Vinci's notebook: The Codex Arundel: Treasures in focus**, London: British Library, 2008, pp. 20-21; BARONE, *op. cit.*, 2011, entries 33-35, pp. 37-39; BARONE, Juliana, "Studies for a perpetual motion wheel and notes on water" and "Studies for a perpetual motion wheels", in: BARONE, Juliana (Ed.). **Leonardo da Vinci: A mind in motion**, London: British Library, 2019, entries 42-43, pp. 146-48; KEMP, Martin. "Leonardo's book of negative demonstrations: Circular motion and the *perpetual wheel*". In: BARONE, *op. cit.*, 2019, pp. 216-23.

8 The sheet is related to others in the Codex Atlanticus, such as ff. 94r, 138r, 139r. For comments on f. 139r, see BARONE, *op. cit.*, 2011, entry 5, p. 19. For the dating of all the Codex Atlanticus sheets discussed in this essay, see MARINONI, Augusto. "Cronologia e ordinamento dei fogli del Codice Atlantico", in: MARANI, Pietro C. (Ed.), **Il Codice Atlantico di Leonardo da Vinci**, Florence: Giunti, 2004, pp. 75-77.

9 Codex Atlanticus, f. 267v, is related to ff. 754r and 1061r.

issues around propulsion power.

More specifically with respect to his Milanese period, it was at the Sforza court that he enjoyed direct contact with the civil and military architect and engineer, Francesco Di Giorgio, as well as with mathematician Luca Pacioli. With Di Giorgio, Leonardo not only extended his technological knowledge and consulted books in the famous library of Pavia, but also treasured in his own library a technical treatise by Di Giorgio dealing not least with hydraulic engineering matters [10]. With Pacioli, Leonardo developed a long-lasting friendship and collaboration, improved his knowledge of mathematics, gained precious assistance in the study of key classical authors and developed his studies of proportion, geometry and stereometry. Unsurprisingly, it was also in Milan that we begin to witness unprecedented levels of dynamism in his artistic work. Cases in point are his portrait of the *Lady with an Ermine* (Cracow, Czartoryski Museum) and his mural depicting the *Last Supper* (Milan, St Maria delle Grazie). His rendering of human figures becomes increasing lively and kinetic, as if they were about to change position in the course of their action and further interact with other figures or with the viewer. They express the qualities of *moto corporale* and *moto mentale* both of which Leonardo would later theorise in his Treatise on Painting (Vatican City, Biblioteca Apostolica Vaticana)[11].

Similar links across his artistic, theoretical and engineering endeavours

[10] Codex Ashburnham 361, Florence, Biblioteca Medicea. For the manuscript, see FIRPO, Luigi and MARANI, Pietro. C. (Eds.), **Il Codice Ashburnham 361 della Biblioteca Medicea Laurenziana di Firenze: Trattato di architettura di Francesco di Giorgio Martini**, Florence: Giunti, 1979.

[11] For the *Treatise on painting*, also known as *Libro di pittura* or Codex Urbinas Latinus 1270, see PEDRETTI, Carlo (Ed.), **Leonardo da Vinci: Libro di pittura**, Florence: Giunti, 1995. For Leonardo's ideas on motion, see BARONE, Juliana, "Illustrations of figures by Nicolas Poussin and Stefano della Bella in Leonardo's *Trattato*", **Gazette des Beaux-Arts**, CXXXVIII, July-August, 2001, pp. 1-14; BARONE, Juliana, "Poussin as engineer of the human figure: The illustrations for Leonardo's *Trattato*", in: FARAGO, Claire (Ed.), **Re-reading Leonardo. The Treatise on painting across Europe, 1550-1900**, Farnham: Ashgate, 2009, pp. 197-235; BARONE, *op. cit.*, 2011; KWAKKELSTEIN, Michael and PLOMP, Michiel, **Leonardo da Vinci: the language of faces**, Haarlem: Teylers Museum, 2018; and most recently MARANI, Pietro C., "The *movements of the soul* in Leonardo's painting and theory", in: BARONE, *op. cit.*, 2919, pp. 224-37.

emerge from Leonardo's second Florentine sojourn. During the years in which he worked for the Florentine Republic, he delves into water engineering projects, this time taking as his subject the canalisation and deviation of the course of the Arno. He also applies himself to his geometry book 'On transformation', which he himself dates as 1505, and to a treatise on the 'Flight of Birds' (Turin, Biblioteca Reale), datable to 1505-06, one of the central themes of which being the study of shifts in the centre of gravity of birds to explain the mechanics of ascend and descend. Leonardo's studies of flight are comparable to his investigation of human motion, as he uses the geometry of balances in both his studies of the human body and of the flight of birds in order to disclose the rationale behind changes in the distribution of weight[12]. Major artistic projects he started conceiving in this period include the *Battle of Anghiari* and the *Leda* (both lost), and the *Virgin and Child with St Anne* (Paris, Louvre), reaching high levels of visual and intellectual complexity in the expression of motions and emotions. They were composed alongside the core of his theoretical writings on water dynamics in the Codex Leicester (Seattle, Collection of Bill Gates) and on human motion for his projected Treatise on Painting.

Turning to Leonardo's perpetual motion drawings, they can be seen to belong to two main groups. One is linked to the invention of a screw pump attributed to Archimedes that could scoop up water and push it up a hill; the other consists of overbalanced wheels. The latter is the most common in Leonardo's studies and can in turn be considered according to some three basic types: 1) a wheel with fixed weights at the end of mechanical arms, which is a model derived from earlier variants illustrated by Villard de Honnecourt and Taccola among others[13]; 2) a wheel with free spherical weights running along compartments in the shape of segments of a circle, and which is also derived from earlier models represented by Taccola and

[12] For a study of the Codex on the Flight of Birds, its structure and composition, see BARONE, Juliana and KEMP, Martin, "What is Leonardo's Codex on the flight of birds about?", in: O'GRODY, Jeannine A. (Ed.), **Leonardo da Vinci. Drawings from the Biblioteca Reale in Turin**, Birmingham (Alabama): Birmingham Museum of Art, 2008, pp. 97-110.

[13] For this model, see Codex Atlanticus 1062r, wheel 'A'.

Di Giorgio[14]; 3) a wheel in which either free spherical weights or liquids (such as water, wine, oil or molten silver) run through channels or fill compartments that can be dynamically emptied through pipes. Each of these three basic types of overbalanced wheels is typically developed by Leonardo providing a wide range of variations. The taxonomy and interrelationship of his perpetual motion studies, with possible implications for a fine-tuning of their dating, is the subject of a forthcoming work[15]. Here, our attention will now focus on a sheet in the Codex Atlanticus, f. 1062r-v [Fig. 1], as this sheet can help us discern important links between his studies of perpetual motion and his artistic practice, and place them within the broader context of his creative work.

Traditionally dated to c. 1493, the Codex Atlanticus sheet displays all the three basic types of overbalanced wheels outlined above. While the verso shows a highly finished large wheel with compartments filled with water, air and lead[16], the recto has five smaller drawings of overbalanced wheels: 'A', 'B', 'C', 'D' and 'E' [Fig. 2]. Wheel 'D' is the smallest and least finished of them, but both this wheel and wheel 'C' are accompanied by spontaneous sketches showing options for their channels. The sheet also contains a drawing of a human arm bent at 90 degrees, and three texts, two of which are related to the wheels next to them while the third (near the middle of the sheet) is a riddle. The irregular marks of a cut out reflect the work of a later collector who extracted a motif from the sheet[17].

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[14] For this model, see Codex Atlanticus 1062r, wheel 'B'.

[15] For an overview of Leonardo's studies of perpetual motion, see BERNARDONI, "A Never-Ending Quest: Leonardo's Study of Perpetual Motion". In: BERNARDONI, *op. cit.*, 2019, pp. 24-35.

[16] For Codex Atlanticus 1062v, see GALLUZZI, *op. cit.*, 2006, p. 250; and BARONE, *op. cit.*, 2011, entry 34, pp. 38-39.

[17] The motif has been identified as the head of an old man and is now in Windsor, Royal Collection Trust, RCIN 912466.

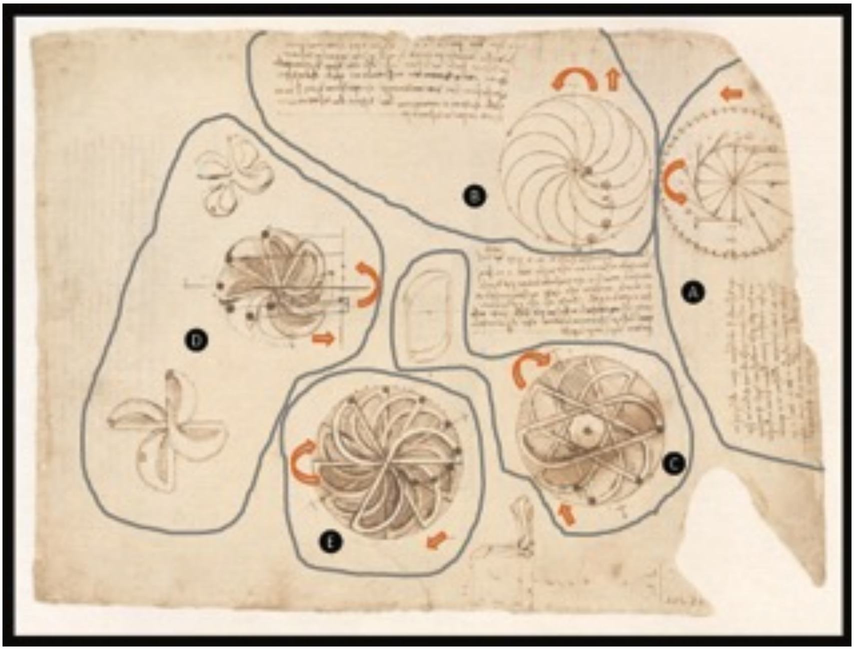

Figure 2
Leonardo da Vinci
Studies of overbalanced wheels, Codex Atlanticus, f. 1062r
Pen and ink, c. 1495
Arrows point the right side up and rotation-will
Photo credit Veneranda Biblioteca Ambrosiana / Metis e Mida Informatica / Mondadori Portfolio

Looking more closely at these perpetual motion wheels, we can see that together with the fact that some are more finished than others and that some have accompanying details or explanatory texts while others do not, some turn clockwise while others describe an anticlockwise movement. Wheel ‘A’, composed of twelve articulated arms with a fixed weight at the end of each, turns anticlockwise, as does wheel ‘B’, which is subdivided into twelve equal segments of a circle, each containing one free spherical weight. Similarly, wheel ‘D’, containing eight continuous channels with six free spherical weights, produces an anticlockwise movement. By contrast, wheel ‘C’, showing four continuous channels fixed around an octagonal drum, each with one free spherical weight, turns clockwise. And so does wheel ‘E’, composed of four sets of a three-looped channel, each containing two spherical weights; it describes a clockwise movement. Also worthy of notice is that the sheet needs to be rotated no fewer than five times for each of the five wheels to appear the correct side up. All these elements provide us with significant pieces of evidence for gauging Leonardo's working methods and design process.

Leonardo's perpetual motion drawings are far from dry or little related to his broader artistic practice and inventive methods. A case in point is provided by the highly finished wheel 'B' in the Codex Atlanticus. It is no coincidence that this model, carefully drawn in pen and ink with the aid of a ruler and a pair of compasses, can be shown to be closely linked to other wheels rendered in different media and levels of finish across sheets from different manuscripts. For instance, it appears in a quick sketch in red chalk in MS H, f. 114v, datable to c. 1493-94, though in this case the wheel turns clockwise and is composed of only six segments. An analogous red-chalk sketch is found in Codex Forster III, f. 12v, which is normally dated to c. 1490-93. The wheel similarly turns clockwise and is subdivided into six parts, but in this case the segments of the circle are sectioned by straight radial lines which render some materiality to the basic geometrical structure. And the same model is seen in Codex Madrid I, f. 176r, datable to 1493-97. It is now in pen and ink, subdivided into as many as sixteen parts and turning anticlockwise. If more elaborate than the red-chalk sketches in MS H and in the Forster, the Madrid wheel is not as highly finished as wheel 'B' in the Atlanticus.

The use of red chalk in Leonardo's perpetual motion drawings has not been previously examined. But there are other instances in his manuscript legacy in which we find both free-hand and more finished red-chalk sketches, such as in Codex Atlanticus, f. 921v, datable to c. 1490. Examples also emerge throughout Codex Forster II, ranging from mathematical annotations to geometrical and mechanical drawings. In fact, it is no coincidence that the use of red chalk in Leonardo's technical work appears around the same years in which he started using the medium in his artistic work, such as in his famous studies for the heads of the apostles in the *Last Supper* of the mid-1490s[18]. And if his use of red chalk in technical drawings—and more specifically in his perpetual motion studies—might seem unexpected as it does not offer absolute technical precision, it newly reveals the spontaneity and rapidity with which Leonardo could render mechanical forms when thinking about the overall structure and logic of the movement.

The same model shown in wheel 'B' in the Codex Atlanticus—and in MS H, in the Forster and Madrid Codices—re-appears very highly finished and fully integrated with an explanatory text in Codex Forster II, f. 91v, traditionally dated to 1495-97 [Fig. 3]. Here the wheel is subdivided into twelve segments and turns anticlockwise. The calculated construction of its underlying geometry can be partially reconstructed based on the archaeological marks left on the paper as part of Leonardo's design process. This is particularly the case with the presence of incised lines, most of which were not covered up by pen. Some were traced by the sharp point of a stylus running along a ruler, others with the dry needle point of a pair of compasses. For instance, there are twelve radial lines that have not been passed over with the pen, with the exception of the small portions that meet the outer segment of each circle. Similarly, there is a smaller circumference (half the outer circumference of the wheel) that was not redrawn in pen, but which is crucial for explaining the wheel's functioning. The intersection of the smaller circumference with the central axis of the wheel creates a point which Leonardo uses for the centre of what he calls the 'contrary circle *a*, *n*, *m*'. The 'contrary circle', Leonardo explains in the text, indicates the ascending trajectory of the weights, which, in turn, works against the 'perpetual' motion of the wheel.

[18] See for instance the Study for the Head of St James the Greater and a Corner Pavillion of a Castle, Windsor, Royal Collection Trust, RCIN 912552.

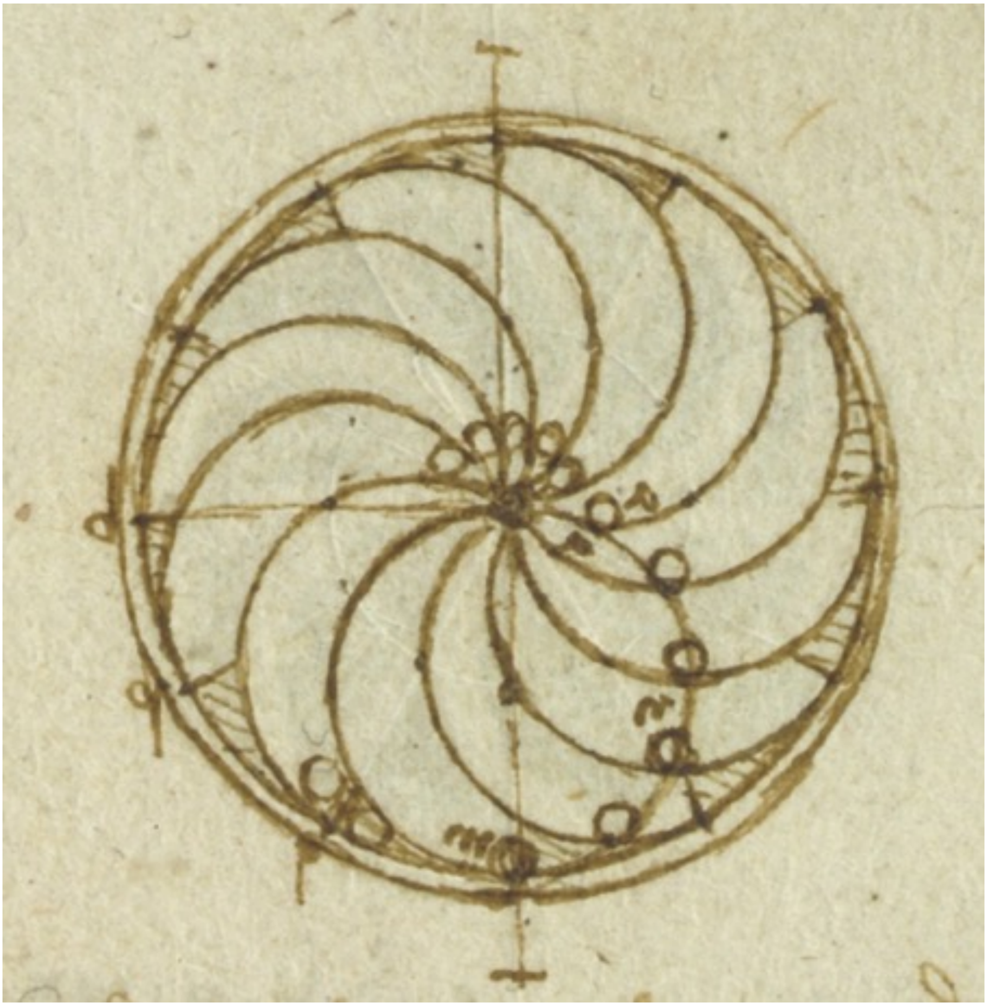

Figure 3
Leonardo da Vinci
Study of overbalanced wheel, Codex Forster II, f. 91v
Pen and ink, c. 1497-1500
Photo credit Victoria and Albert Museum, London

Particularly interestingly from the point of view of Leonardo's graphic techniques, is that he counted on the transparency of the paper to draw the wheel that appears on the other side of the sheet, that is, Codex Forster II, f. 91r [Fig. 4]. The wheel on the recto is similarly subdivided into twelve parts and has the same 'contrary circle', but it turns clockwise as the transfer of the design from verso to recto produced a reversal of the basic structure. Similarly, he made use of the radial lines on the verso to achieve a variation in the internal structure of the wheel on the recto, which is composed of four sets of a three-looped channel in the manner of turbines. These two perpetual motion wheels, on verso and recto of the Forster, are, in turn, very similar to wheels ‘B’ and ‘E’ in the Codex Atlanticus, but more finished in terms of both overall design and page layout, being represented in the correct way up and above their explanatory texts. They reflect moments of consolidation of Leonardo’s thoughts and may well postdate the wheels on the Codex Atlanticus sheet.

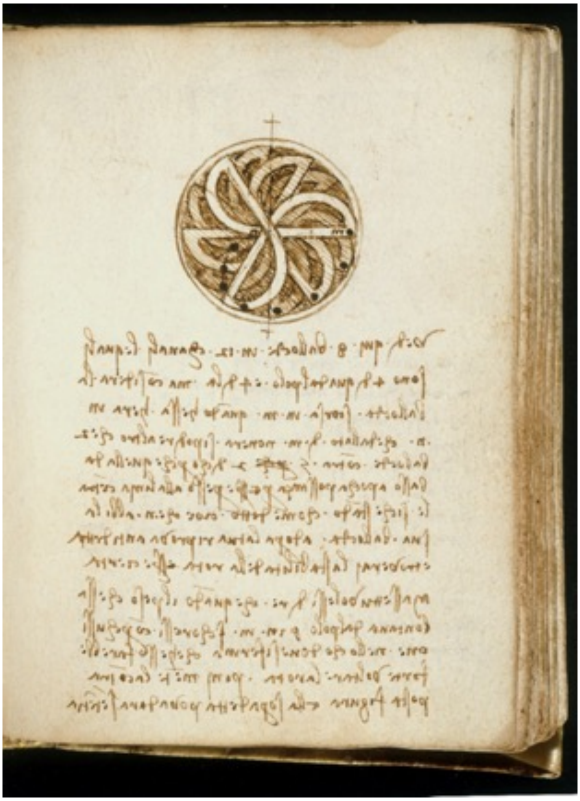

Figure 4
Leonardo da Vinci
Study of overbalanced wheel, Codex Forster II, f. 91r
Pen and ink, c. 1497-1500
Photo credit Victoria and Albert Museum, London

Leonardo's recourse to transfer technical designs while exploring variations in structure is a procedure consistent with graphic methods he explored extensively in his artistic practice. We witness his use of such procedures in studies as early as those showing the *Virgin and Child with a Cat*, datable to c. 1478-81[19], where the transparency of the paper allowed him to trace from verso to recto the main outlines of the image. The traced image appears in reverse on the other side of the sheet and was re-worked as part of his process of searching for a more final arrangement of the individual figures and overall composition. Analogous procedures also emerge from his mature studies, such as the famous sheet of the *Virgin and Child with St Anne with hydraulic studies*, a sheet which is usually dated to c. 1506-08[20], not least because of the drawing of a waterwheel and the fragments relating to the construction of dams. In addition to the interesting co-existence of artistic and technological studies, the sheet offers one of the most extraordinary examples of Leonardo's 'brainstorming' technique. The main sketch shows several alternatives for the composition. The rich and dynamic overlay of lines for the positioning of the figures had become so dense that Leonardo transferred his favoured composition by pressing the sharp point of a stylus along the main outlines. The transferred image appears in reverse on the other side of the sheet, which he subsequently used as a reference for his large-scale *St Anne* cartoon (London, National Gallery). If we then turn back to the Codex Atlanticus sheet, in which we have observed two wheels describing a clockwise movement and three turning anticlockwise, and the need for the rotation of the paper no fewer than five times for each wheel to appear the correct way up, it seems increasingly likely that Leonardo made use of transfer techniques when designing them on this 'type' sheet, a sheet which typically reveals his continuous thinking while searching for more finished

[19] London, British Museum, inv.1856-6-21-1. For the drawing, see KEMP, Martin and BARONE, Juliana, **I disegni di Leonardo da Vinci e della sua cerchia nelle collezioni della Gran Bretagna**, Florence: Giunti, 2010, entry 17, pp. 61-62; and BAMBACH, Carmen C., **Leonardo rediscovered**, New Haven/London: Yale, 2019, pl. 3.27.

[20] London, British Museum, inv.1875-6-12-17. For the drawing, see KEMP and BARONE, *op. cit.*, 2010, entry 21, pp. 66-69; BAMBACH, *op. cit.*, 2019, pl. 9.14.

solutions.

All in all, Leonardo can be shown to have nurtured an interest in perpetual motion throughout his life. The principle of disruption of balance underpins his understanding of both mechanical and natural motion, from the movement of the arms of a balance and of perpetual a motion wheel, to that of the human body and the flight of birds. Although he came to realise the impossibility of perpetual motion, he kept on exploring potential possibilities. His perpetual motion drawings are both numerous and varied in forms of expression. The study of their multiple relationships and of the underlying archaeology of their construction clearly places them within his broader artistic practice, creative methods and drawing techniques, and paves the way for a more comprehensive re-evaluation of his technical drawings.